Renewable and Sustainable Energy Reviews 39 (2014) 679–685

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Status and prospects of rural biogas development in China

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A R T I C L E I N F O

Article history:
Received 18 March 2014
Received in revised form
9 July 2014
Accepted 13 July 2014
Available online 5 August 2014

Keywords:
Fermentation material
Fermentation technology
Biogas development model
Rural development
China

A B S T R A C T

Developing biogas capacity is a key pillar in China's rural sustainable development program. The very dynamic transition of the rural socio-economic platform on which the current biogas development strategy has been based will require significant adjustments in material, technology and supply. The changes of socio-economic status, the problems of resent state and prospects of rural biogas development in China, including fermentation material, fermentation technology, development model and comprehensive utilization of biogas, are discussed in this paper. The results of our analysis indicated the full use of straw as a raw material will be the direction of biogas development in China. Dry methane fermentation will become an important method in the large scale production of biogas from agricultural wastes. The central supply model is the future biogas development model in rural China. It is with broad market and great potential to produce commercial fertilizer from biogas residue. Using biogas to generate electricity has become a new and efficient way to use biogas.

Contents

1. Introduction

It has been widely accepted that providing adequate, clean and affordable energy to rural residents is essential for eradicating

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http://dx.doi.org/10.1016/j.rser.2014.07.119
1364-0321/

poverty, improving human welfare and raising living standards worldwide [1]. Biogas technology is being seriously promoted as an important option to meet the growing energy demand of rural areas in developing countries [2]. Rural industries in India suffer from acute power shortages and irregular supplies and there is the necessity to install large capacity biogas plants in rural areas as enterprises from which they can meet their energy requirements [3]. Today India has about 2 million biogas plants of various sizes and capacities ranging from 1 m^3 to about 150 m^3 [4]. China is one of the world's largest energy consumers that imported 1.63 × 108 t of crude oil in 2007, and the dependency on foreign oil reached to 46.6% [5]. As a renewable energy, biogas is not only an important part of the development of rural new energy, but also an important aspect of sustainable development in China [6]. The Chinese rural biogas development model primarily takes the form of small-size household biogas pools. Animal manure is the main fermentation material. Household biogas construction has developed rapidly in China's rural areas since the 1990s. For example, there were 4.9 million rural households using biogas in 1996, 12.3 million households in 2003, by 2008, the number had increased to 30.5 million households, an annual increase of 29.1% [7].

The socio-economic status significantly influenced the development of biogas industries in rural China. For example: Intensify the animal production will significantly affect the household biogas fermentation materials in rural China; the change of the built environment of villages will affect the biogas development model in rural China. For this reason, we should adjust the biogas development strategy according to the changes of socio-economic status. It will be helpful to the sustainable development of biogas in rural China.

The purpose of this paper is to analyse the changes of socio-economic status and the problems of resent state of rural biogas in China, including fermentation material, fermentation technology, development model and comprehensive utilization of biogas. And to compare the difference between straw and manure as biogas fermentation material, wet and dry anaerobic fermentation, household biogas model and central-supply model. We highlight the future trends of rural biogas in China in this paper, we attempt to answer the following:

- What is the future biogas fermentation material in rural China?
- Which biogas fermentation technology do we choose in future?
- What is the future biogas development model in rural China?
- How to use the biogas and residue and slurry in future?

2. Discussion

2.1. Fermentation materials

2.1.1. A shortage of raw material of rural biogas in China

Animal manure is the main raw ingredient of rural biogas in China. To set up a biogas digester of 8 m^3, the amount of animal manure produced by three or four pigs is sufficient to maintain the gas offer [8]. As the development of the urbanization, the rural labour migration, and the large-scale development of the intensive breeding industry, the rural disperse culture decrease day by day as a result. At present, there are about 2500 piggeries with annual slaughter amount more then ten thousands pigs, which cover 10% of the total amount in China. In future ten years, the medium and small scale piggeries with annual slaughter amount between 1000 to 10000 pigs will be the main popular types. It is estimated that by the year of 2020, annual slaughter amount offered by piggeries (or enterprises), with annual slaughter amount more than 1000 pigs, will cover 50% the total amount in China [9]. Some households choose not to culture throughout the whole year, which has resulted in the separation of livestock from people in rural areas [9,10]. Taken together, the shortage of raw material for rural biogas production will significantly affect the future development of the Chinese rural biogas project.

2.1.2. The advantage of developing straw biogas

Straw will replace animal manure as the main raw material of biogas, which is ubiquitous in the whole rural area. Crop straw is a kind of biomass which can be rich in organic by 80 to 90 percentage. Roughly 700 million tons annually, half of which is not used effectively [11]. The majority of the crop straw is burned as fuel either in homes or fields, a process which not only pollutes the environment, but also wastes energy. Some of the crop straw are being used as feed or returned back to field again. Fermenting the crop straw to produce biogas would both decrease rural environmental air pollution and contribute to solving the problem of the shortage of rural energy.

The data for the characters of straw and manure as biogas fermentation material are shown in Table 1. Crop straw has several advantages over animal manure [12]: (1) It is widely distributed in sufficient quantities throughout China; (2) The crop straw contains less water so that fermentation residues can be directly applied as organic fertilizer in contrast to animal manure residue and slurry which are hard to use and deal with; And they will pollutes the environment for the second time if discharged without being dealt with. (3) The crop straw can be stocked over the long term and efficiently transported.

As a biomass resource, straw is applied for gasification widely except methane fermentation. However, it is very hard to promote this project in China. Straw gasification is the process of transfer the straw to be air fuel. Data the difference between straw biogas technology and straw gasification are shown in Table 2. Compared with straw gasification, straw biogas has the advantage of the following points [13]: (1) Straw biogas technology is the biological process with mild reaction conditions, which can ferment at the room temperature. And the maximum fermentation temperature does not exceed 55 °C. High efficiency for the energy input and output, which is convenient to the production management and more suitable for practical application. While straw gasification technology is thermal reaction process, required temperature above 400 °C, with high energy input and low energy efficiency

Table 1
The characters of straw and manure as biogas fermentation material [12].

Parameters	Straw	Animal manure
Quantity	Widely distributed in sufficient quantities throughout China	Shortage
Stock	The straw can be stocked over the long term	Animal manure hard to long term stocked
Transport	The straw can be efficiently transported over the long term and	Animal manure hard to long term transported
Fermentation residues processing	The crop straw contains less water so that fermentation residues can be directly applied as organic fertilizer	Animal manure residue and slurry which are hard to use and deal with; And they will pollutes the environment for the second time if discharged without being dealt with

Table 2
The difference between straw biogas technology and straw gasification [13].

Parameters	Straw biogas technology	Straw gasification
Temperature condition	Room temperature maximum fermentation temperature does not exceed 55 °C	Temperature above 400 °C
Reaction process	Biological process	Thermal reaction process
Efficiency	High efficiency	Low efficiency with high energy input and low energy efficiency ratio
Pollution	A clean production process, zero waste emissions	dust, noise or tar
Application	Easy to put into practice	Hard to put into practice

ratio. Also it is not easy to control and to manage the production, so it is difficult to apply this style in rural area. (2) Producing biogas from straw is a clean production process which benefits environmental protection. The fermentation residue is high-quality organic fertilizer which does not produce any harmful by-products, and can achieve zero waste emissions fulfilling the goal of complete resource conversion. Unlike the process of straw gasification production it produces no dust, noise or tar. (3) Biogas made from straw is with high heat and better quality. The calorific value of flammable gas made from straw is 50% to 60% of that of biogas, with low grade, low efficiency to storage and transmission, and hard to put into practice.

2.1.3. The development of the straw biogas technology

In the United States, Greece, Sweden and some developing countries studies on straw as a raw material to produce biogas has a long history [14–16]. In China, in the 1960s, straw was served as a major fermentation of raw materials for biogas engineering practice [17]. In the late 1980s, the application of straw fermentation was rare having come almost to a standstill in the country. Straw contains large amounts of cellulose and lignin. When the straw is put directly into biogas fermentation, with slow straw decomposition, low utilization of raw materials, and so prone to the phenomenon of crust, and the digester start slow (slow fermentation), and gas production is relatively low [18,19]. In recent years, the Chengdu Institute of Biology of the Chinese Academy of Sciences and Beijing Hebaiyi Ecological Energy Technology Development Co., Ltd. has made significant breakthroughs in straw biogas technology. Using bio-fermentation technology and modern production equipment they developed a "straw preconditioning agent" (LV JieLing), which softens and loosens the internal fiber structure of the straw. This benefits anaerobic decomposition bringing forward digester start-up time by 4 to 8 days when fermenting in a pond and increases gas production by as much as 40%. And then all these problems of rural biogas digesters can be effectively solved that the shortage of raw materials, start slow, low gas production [8,20]. Since 2005, the Ministry of Agriculture has organized relevant research institutes and enterprises to begin straw biogas technology R&D and demonstration. And in Jiangxi, Shandong, Jiangsu, Zhejiang, Sichuan, Henan, Beijing, Hebei, Liaoning, Heilongjiang, and Dalian, 11 provinces and cities of more than 100 counties began pilot projects. In 2007, the Ministry of Agriculture placed straw biogas production technology at the top of "Ten energy-saving technology projects" of the Chinese agriculture and rural area. Therefore, the full use of straw as a raw material will be the direction of biogas development in China.

2.2. Fermentation technologies

2.2.1. Problems of anaerobic wet fermentation

Biomass anaerobic fermentation technology can be divided into two types, wet and dry. The content of the TS is below than 10% in anaerobic wet fermentation reaction system generally [21]. Anaerobic wet fermentation is the mainstream of the treatment on organic pollutants in biogas production currently with the advantage of high speed on fermentation, mature technology of construct and management, and convenience input and output for the material [22]. Some problems remain unsolved with agriculture and solid waste, such as: depletion on large amounts of clean water, low concentration of the fermentation product, difficulty on the dehydration, difficult to be effectively used of the fermentation product [23]. These problems restrict the role of this technology in the process of the utilization of agricultural wastes. In the fermentation of straw the straw floats in the digester forming a crust which results in poor biogas production. Besides, pond type of the wet biogas itself is not appropriate for outputting of the straw fermentation, which caused the difficult of expanding the application of straw wet fermentation technology to produce biogas [24].

2.2.2. Features of anaerobic dry fermentation

Anaerobic dry fermentation, (anaerobic digestion of high solids), is the methane fermentation process of solid organic waste as raw materials, in the absence of flowing water, in which the TS content reaches 20–30% [21,25]. Normally, about 20% dry matter content is being more appropriate condition [26].

Anaerobic dry fermentation ensures that livestock manure and crop residues can ferment normally in the case of higher dry matter concentration to generate clean energy (biogas) and quality organic fertilizer reached zero emissions, which meets the needs for the good environment, clean energy and quality organic fertilizer in Chinese vast rural areas [27]. Currently the technology is widely used to treat municipal waste, livestock manure, crop straw, with the advantage of water saving, easy management, high biogas production, low processing cost, which has become a research hotspot of anaerobic fermentation technology [28]. Domestic and foreign large number of studies show that the effects of methane dry biogas production is well [29,30]. Chinese researchers have studied the methane dry fermentation process with less nutrient losses [31,32]. Foreign researchers have studied the health situation on dry methane fermentation residue with fine sterilization to kill eggs of bacteria [33]. The difference between wet and dry anaerobic fermentation in Table 3. Compared with anaerobic wet fermentation, anaerobic dry fermentation has the following features [19,34,35]: First, there is no need for a large input water. Second, pretreatment needed. As the complex structure and the difficulty to decompose of the crops straw itself, the pretreatment for the crop straw is need before it was put into pool, which included grinding, zymocyte agent added, reactor and retting. The straw can be put directly into the fermentation pool for anaerobic wet fermentation. Third, post-processing is easier. Because less water is used there is little sewage discharge. The fermentation residue from anaerobic dry fermentation can be used without dehydration as organic fertilizer. In addition, the sulphur content of biogas produced using anaerobic dry fermentation is

Table 3
The difference between wet and dry anaerobic fermentation [19,34,35].

Parameters	Wet	Dry
Water require	A large clean water	Less water
Pretreatment	Don't need pretreatment. The straw can be put directly into the fermentation pool for anaerobic wet fermentation	Need pretreatment. As the complex structure and the difficulty to decompose of the crops straw itself, the pretreatment included grinding, zymocyte agent added and reactor
Post-processing	Need dehydration and desulfurization	Without dehydration and desulfurization
Device	Need to install a blender in the fermentation room	Simpler than anaerobic wet fermentation
Energy consume	Consume 30–45% energy made by itself	Consume 10–15% energy made by itself

Table 4
Biogas dry fermentation facilities in China.

Year	Biogas dry fermentation device
1970s	Straw biogas dry fermentation device with one-time input materials
1980	Wet and dry co-fermentation systems
1986	Cylindrical seal dry fermentation biogas device
1989	Automatic discharging device of biogas dry fermentation
2004	Stir device of biogas dry fermentation
2004	Tank heating insulation device of biogas dry fermentation with high temperature

lower than that of anaerobic wet fermentation. These mixed gases can be used directly without the need of desulfurization. Fourth, compared with the device of anaerobic wet fermentation that of anaerobic dry fermentation is simpler. As the raw material has been pretreated there is no need to install a blender in the fermentation room for adding other inoculums. Fifth, anaerobic dry fermentation consumes 10% to 15% less energy made by itself in the winter, with about 30% of that consumption for anaerobic wet fermentation; even reach to 45% consumption in cold winter of northern area, which greatly limits the biogas technology promotion in these cold areas.

2.2.3. *The development of dry fermentation technology*

As the high dry matter concentration of raw materials of fermentation, dry fermentation has the features of difficult to output and input for raw material, uneven of heat and mass transfer, and acidosis, which are the technical difficulties of dry fermentation. From 1940s onward, Germany, France and Algeria began to use batch-type dry fermentation technology [27]. In the 1980s, studies on dry fermentation were undertaken in the Netherlands, Switzerland, Burkina Faso, Niger and other countries [27]. In the 1990s, there are heavily subsidized for the research on the new batch of dry gas production in Germany; and in the end of 1990s, this process and equipment through the pilot. In 2002, industrial equipment was produced and put into practical operation [36]. Foreign anaerobic dry fermentation technology has matured. Many large-scale methane dry fermentation systems have been brought into production. These include garage dry fermentation, air bag systems, leach ate storage bucket system, and dry joint type systems [37–39].

Household dry fermentation studies in China began in the 1980s. In 1988 the EPA Energy Ministry of Agriculture successfully appraised an automatic discharge dry fermentation biogas device and approved the corresponding process of semi-continuous dry [40]. Mr. Ma Yunrui developed dry fermentation tank of separation of gas constant, by which the biogas produced can meet energy needs of two meals a day for cooking of the family of four person (6 month to 10 months) and lighting (5 months to 11 months) [41]. At present, dry methane fermentation will become an important method in the large scale production of biogas from agricultural wastes [16,33]. A chronology of biogas dry fermentation facilities in China is shown in Table 4.

2.3. *Rural biogas development models*

2.3.1. *Constraints in the development of the household biogas model*

The Chinese rural biogas development model primarily takes the form of small-size household biogas pools. With the progress of constructing new countryside and the optimization of agricultural industry structure, the further development of Chinese rural' biogas utilization meets certain constraints currently. Several factors currently contribute negatively on the small-size household biogas model. First, the breeding scale of rural livestock affects production. In recent years, due to the optimization of the agricultural industry structure, there are fewer and fewer single families in rural areas that breed livestock by themselves due to high costs, the difficulty of disease prevention, the instability of the market, and a falling profit margin. Large-size breeding facilities are gradually increasing in number. The resulting separation between humans and livestock mainly affects the collection of livestock excrement as a raw material in the fermentation process [42]. (2) The built environment of villages is also changing. Some houses in the countryside are built very close to each other and the resident size is small, thus there is not enough room to build biogas pools. The construction of biogas production plant in villages is thus restricted to a certain degree [43]. (3) Immigration from the countryside to cities also affects the situation. Many young men in villages leave to seek paid employment leaving behind children, women and seniors whose physical strength and capability are relatively weak, making it difficult for them to build, use and manage the pool by themselves [35]. (4) At present, most household biogas pools in China are built underground. The fermentation is conducted under normal temperatures that mainly rely on natural ground and air temperatures. The device itself does not provide any measures to raise the temperature. The low temperature of the pools leads to low efficiency and low conversion of raw materials, thus they cannot meet the needs of annual gas consumption. At the same time, because of the disequilibrium in the fermentation temperature, there is too much biogas to use in summer and too little to use in winter creating seasonal waste and shortage. (5) There is an overlap in device investment and waste of resources. First, household self-built biogas pools cause an overlapping investment in the device; second, the high cost in managing and maintaining those sporadic pools and the shortage of trained professionals result in inefficient use of many biogas pools that have already been built, which affects the farmers' commitment to using biogas; thirdly, it causes waste in raw materials and gas production. The smooth running of biogas pools needs the proper supply of fermentation materials. A shortage in materials will cause insufficient gas production, while excessive

materials will cause a surplus in gas production [44]. (6) Sanitation affects the use of biogas digestors. Household biogas pools are built on the basis of each family breeding its own livestock, which means the livestock's feeding environment cannot be separated from the human living environment. Therefore, some kind of zoonosis diseases, such as aftosa, bird flu, brucelliasis and porcine cysticercosis, may cause cross-infection between humans and livestock. This creates tremendous obstacles in epidemic prevention and control. The excess manure stacked on streets also greatly affects livestock health as well as the quality of human living space.

2.3.2. Advantages of central-supply pattern

For the development of Chinese villages' household biogas utilization, it is necessary to adjust the exploiting idea. Since 2005, biogas experts in China have promoted a village-level biogas central-supply model. The village-scale production of biogas is another trend that will affect the future development of biogas. The central supply model requires building large-scale fermentation and storage devices village by village to supply biogas uniformly, or combining the construction of biogas and industrial scale livestock breeding. In this way planners can take advantage of the large amount of manure and build medium-size or large-size biogas projects that will deliver biogas to homes through a pipe network [45]. The central supply pattern can solve the problem that farmers are not able to use biogas due to the lack of fermentation materials, the shortage of labors and short in pool-building condition. This model conserves land, reduces costs, improves efficiency and extends the service life of biogas pools [46]. For example, a 50 m^3 biogas pool covers an area of around 50 m^2, which is capable of supplying the basic fuel requirements of daily life for 15 families. A biogas pool of 8 m^3 (also supplying 15 families) covers an area of over 150 m^2 [43]. The land saved can be used for farmers to do yard landscaping and greening, or plant flowers and fruit trees for extra income. The central supply pattern adopts a market operation, charging a given fuel and maintenance fee to ensure the smooth running of centrally supplied biogas. This pattern will provide professionals to organize and manage biogas production, supply and maintenance, assuring efficient day-to-day running of the biogas digesters. In this way, the security of the entire supply system can be guaranteed.

2.3.3. Development of a central-supply pattern (example introduction)

Fig. 1 shows biogas central-supply pattern [47].

Address: Luimingying, Daxing District, Beijing

State: 251 families, farmers planted 580 acres of organic vegetables, raising chickens 200,000, cows more than 100 head, pigs 3000 head.

Scale: One 100 m^3 biogas digester and one 200 m^3 biogas digester

Biogas production: 800 m^3/d

Biogas residue: 1.4 t

Slurry: 16 t

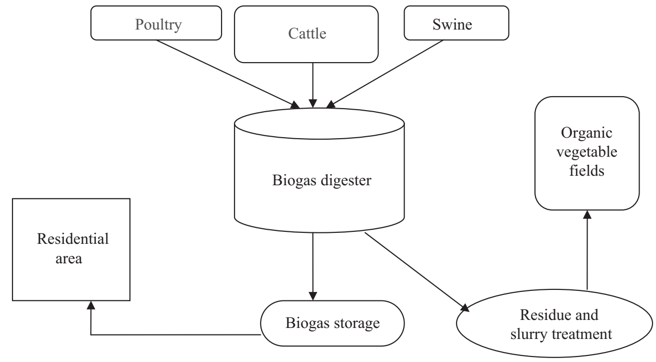

Fig. 1. Biogas central-supply pattern.

2.4. Comprehensive use of biogas in China's rural areas

2.4.1. The present situation

The comprehensive utilization of biogas is an important step in the development of recycling agriculture. This refers to the serial reuse and recycling of biogas and biogas residue and slurry generated by the anaerobic fermentation of organic wastes for raw material, fertilizer, feed, additives and energy of other productive activities. With its capacity to strengthen resource utilization of organic waste and networking of food chain, the niche within ecosystem can be enriched and resources potential can be developed in depth, making efficient and multilevel utilization of limited agricultural resources [48,49].

Most biogas users in China's rural areas haven't received technical training, and are thus unable to integrate biogas technology with eco-agricultural technology. At present, the comprehensive utilization of biogas and its by-products is still at a low level. Biogas is primarily used for fuel. Less than 1% of the potential economic exploitation rate and merely 4% of potential ecological exploitation rate is achieved [50]. In 2005, a total of 6730,900 rural households adopted the comprehensive utilization technology, a figure which accounts for 37.3% of those households using biogas digesters [51].

2.4.2. The development tendency

2.4.2.1. Producing commercial fertilizer from biogas residue and slurry. In China's rural areas, the biogas residue and slurry is used as fertilizer directly without any treatment. Such practice, on the one hand, restricts its wide application because of the inconvenience of application and transportation. Because of the seasonal nature of agricultural production and limited dissolving and absorbing ability of farmland, a significant amount of biogas residue and slurry are discharged directly into the nearby water bodies or farmland, creating a serious threat to the environment, drinking water sources and agricultural ecological safety [52,53]. Such practices ignore both sanitary and safety concerns. Biogas fertilizer in the form of anaerobic fermentation residue not only contains nutrients, but also heavy metals, pesticide residues and pathogenic bacteria. The unbalance of nutrients and the excessive manure load per unit area of farmland caused by the continual application of a kind of fertilizer cause secondary pollution, such as soil phosphate, soil phosphorus leach ate and heavy metal accumulation [54]. The amount of biogas residue increases considerably with the development of biogas projects. So it is with broad market and great potential to produce commercial fertilizer through deep processing of biogas residues, which is of long shelf-life and good effect, convenient to transport and apply, and above all, pollution free.

2.4.2.2. Biogas electricity generation. Farmers only use biogas for heating, cooking and lighting in rural China [55,56]. Generally, an ordinary household biogas digester supplies more biogas than needed when it functions well or in a period of seasonally higher temperatures, resulting in large amounts of waste and additional atmospheric pollution [57]. With the continual development of comprehensive biogas utilization technology, using biogas to generate electricity has become a new and efficient way to use biogas. To generate electricity biogas is used to fuel an engine equipped with an integrated power plant producing electricity and heat. The output of electricity generated changes in accord with the

Table 5
The future potentiality of biogas power generation [58,59].

Parameters	Small-sized biogas power generation	Medium-sized biogas power generation	Large-sized biogas power generation
Unit capacity of generator	3–10 kW	10–50 kW	50–600 kW
Engine	Single-fuel engine (biogas) Dual-fuel engine (biogas/diesel)	Single-fuel engine (biogas) Dual-fuel engine (biogas/diesel)	Single-fuel engine (biogas) Dual-fuel engine (biogas/diesel)
Suitable areas	Remote areas Mountain areas	Livestock farm	Winery sugar mill Sewage Treatment Plant

amount of biogas produced. At present, internal combustion engines and steam turbines are the main equipment used to generate electricity from biogas [55,56]. Although the R&D history of biogas power generation technology in China exceeds 30 years, it mainly focuses on large and medium projects, and most technologies are overseas [58]. However, large and medium biogas power generation projects require large equipment, high cost and an excessive amount of raw material, so it is difficult to promote those projects in China's rural areas [59]. Therefore, in recent years many small biogas generators have been brought on-line and the generating sets have been identified and put into mass production, including biogas fuel engines and dual-fuel engines which partially use biogas. Characterized by complete combustion, low noise, harmless and pollution-free smoke and gas emission, the biogas generators and generating sets with a capacity of 3–10 kW are very popular in rural areas [58]. The development and application of such small-sized biogas power generation contributes to the power supply in remote areas and the production and living energy demand of rural residents by making use of local resources. In addition, it reduces the emission of greenhouse gases and other pollutants into the surrounding environment [55,60]. The future potentiality of biogas power generation is shown in Table 5. As the output of biogas increases, how to best make efficient use of it presents a serious challenge for rural planners.

3. Conclusions

The changes of socio-economic status, the problems of resent state and prospects of rural biogas development in China, including fermentation material, fermentation technology, development model and comprehensive utilization of biogas, are discussed in this paper. As the large-scale development of the intensive breeding industry and the advantage of developing straw biogas, the full use of straw as a raw material will be the direction of biogas development in China. At present, dry methane fermentation will become an important method in the large scale production of biogas from agricultural wastes. Because of the constraints in the development of small-size household biogas model, the central supply model is the future biogas development model in rural China. It is with broad market and great potential to produce commercial fertilizer from biogas residue. With the continual development of comprehensive biogas utilization technology, using biogas to generate electricity has become a new and efficient way to use biogas.

Acknowledgments

Financial support was received from Key lab of Fermentation Resource and Application of Institute of Higher Leaning in Sichuan (Grant no. 2012KFJ002): Research on the key technology of biogas production from white wine waste (Grant no. 2012KFJ002) and Ph.D. Programs Foundation of Yibin University of China (Grant no. 2011B05): Regionalization of Household Biogas Fermentation Temperature and Fermentation Materials in Rural China (Grant no. 2011B05).

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